An Evolutionary Approach to Fission Power

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Abstract

There will be no economic or resource reason to separate plutonium from spent reactor fuel for at least 100 years. Reactor-grade plutonium is as weapons-useable as weapon-grade plutonium. Plutonium in spent nuclear fuel is much more secure against theft than separated plutonium. Reprocessing will not significantly accelerate ultimate waste disposal during the next 50 years since both spent fuel and vitrified high-level waste will be kept in interim retrievable storage for at least that long. There should therefore be a global moratorium on further plutonium separation.

Persistence of the Once-Through Fuel Cycle

It has been recognized from the beginning of the nuclear era that, if fission is to be a major long-term source of energy for humanity, it will be necessary to shift over time from a primary dependence for fuel from U-235 to artificial fissile isotopes bred from more abundant U-238 or Th-232. However, early projections of the quantity of uranium in high-grade ore deposits and of the rate of fission-power-capacity growth turned out to be gross underestimates and gross overestimates respectively.

As a result, the current stage of fission power evolution, in which the simple once-through fuel cycle is the most economical, can be expected to last at least several more decades—even with a resumption of robust nuclear-power capacity growth. In the most recent 1994 OECD analysis, the range for long-term costs for spent-fuel encapsulation and disposal was given as 140-670 ECU/kg, while the range for long-term cost of reprocessing plus vitrified high-level waste disposal was given as 630-1300 ECU/kg.[1] Plutonium-recycle advocates have emphasized the fact that the two ranges overlap but the overlap is small.

In the future, the price of uranium will increase, shifting the economic advantage toward reprocessing and recycle, but the shift cannot be expected to be dramatic. If we assume that 8.4 kg of natural uranium are required to produce 1 kg of LEU (4.4% enrichment, 0.2% tails) and if recycle of the uranium and plutonium recovered by reprocessing reduces this requirement by 25 percent, then an increase in the price of natural uranium to $130/kg from its current price of about $25/kg would increase the relative cost of the LEU fuel cycle by only $220/kg.

According to estimates in the 1993 OECD/NEA uranium survey, however, the world resource of uranium, recoverable at a cost of $130/kg or in other comparably high-grade ores whose recovery cost has not yet been estimated, is about 20 million tons.[2] Beyond these conventional resources are huge unconventional resources. Vast deposits of uranium in sandstone have recently been identified in the U.S., Australia, and Central Asia which could be obtained through in situ leaching at costs estimated at about $50 per kilogram U. Especially arresting are gigantic "roll-fronts" in sandstone deposits in the steppes of Central Asia, in Kazakhstan and Uzbekhstan, which may contain tens of millions of tonnes of uranium.[3] Even given the "high-growth, high-nuclear" scenario put forward in 1992 by the International Panel on Climate Change (IPCC), which would have the world's nuclear capacity increase roughly linearly to 1250 GWe in 2050 and 2700 in 2100,[4] the cumulative consumption of uranium on a once-through LWR fuel cycle would be only 5 million tonnes by 2050, 5.3 million tonnes by 2050, and 17 million tonnes by 2100.[5]

It may be argued that only about 10 percent of the world's estimated low-cost uranium—about 2.1 million tonnes—is in the Reasonably Assured Resources (RAR) category. However, the global rate of uranium consumption is projected to rise to only 75,000 tonnes/yr by the year 2010. At that rate, the current Reasonably Assured Resources will last for about 30 years. At the current spot price of about $25/kg-U there is little economic incentive to make the investments required to upgrade the status of the uranium in the less well explored or undiscovered deposits, except for very high-grade deposits (which are still being found[6]). If more certainty were required, it could be obtained for much lower cost than the many billions of dollars that were wasted in premature efforts to commercialize plutonium breeder reactors.

Of course, reprocessing was originally justified not by plutonium recycle in LWRs but rather by the need to obtain startup plutonium for a second generation of nuclear reactors: fast-neutron plutonium-breeder reactors. However, the price of uranium would have to rise much higher for breeder reactors to become economic. Sixteen years ago, when two Princeton colleagues and I carried out an economic comparison of plutonium-breeder reactors with a once-through LWR and advanced-converter-reactor fuel cycles, we found that, even for a capital cost for the sodium-cooled breeder reactor only 25 percent higher than for the LWR, it would not be competitive with an LWR operating on a high-burnup once-through fuel cycle until the price of uranium climbed to about $400/kg ($60/pound U_3O_8 in 1976$).[7] Even at that price, uranium would account for only about 14 percent of the cost of electricity from an LWR.[8]

Persistence of Reprocessing

Before the long-term economic viability of the once-through fuel cycle became as clear as it is today, some countries launched major reprocessing programs in anticipation of the deployment of plutonium breeder reactors. After 1974, when

India exploded a "peaceful nuclear device" using plutonium separated under this pretext, these reprocessing programs became a source of international controversy. The U.S. adopted an anti-reprocessing position but France, Britain, Russia, Japan, and India maintained their commitments to reprocessing. Why?

In the case of Britain and France, the answer must lie in good part in the foreign exchange that they have been able to earn by reprocessing the spent fuel of other countries—especially Japan and Germany, whose commitments to reprocessing was motivated more by environmental politics than economics. Anti-nuclear activists in Germany and Japan argued that nuclear power reactors in their countries should be shut down because the operators had not found a solution to the spent fuel disposal problem. The operators were then required by their governments to enter into reprocessing contracts with Britain and France to demonstrate that they did have a solution to this problem.

Even at their final high costs, the reprocessing contracts were not a permanent solution to the German and Japanese utilities' problems, however, because they specified that the plutonium and glassified high-level waste would be returned to the country of origin a few years after reprocessing. Return shipments from France to Japan are now beginning and are causing considerable international controversy and embarrassment to the Japanese utilities. And German utilities have been blocked by their environmentalists from bringing into operation the plant that they built in Hesse to produce MOX fuel out of the plutonium separated from their spent fuel in Britain and France.

The German government has therefore recently given its utilities the option of not reprocessing their spent nuclear fuel and they have begun to cancel reprocessing contracts beyond the prepaid contracts with which they helped to finance the construction of Britain and France's commercial reprocessing plants. Instead, they are beginning to store their spent fuel at two central interim storage sites in Germany while they look at long-term disposal options. The Japanese utilities have decided not to enter into additional reprocessing contracts with Britain and France but instead to build their own reprocessing plant at Rokkashio. However, the estimated cost for completing that plant has now become astronomical—about $20 billion—and the utilities would like to abandon it in favor of interim storage. The problem is that they have not been able to find any local government willing to host an interim storage site because of the suspicion that the interim storage will become permanent storage. Therefore, while not abandoning the construction of their first reprocessing plant, the Japanese utilities are building more spent-fuel storage capacity at the site and have postponed the construction of a second reprocessing plant.

Given the prospective decline in their foreign reprocessing business, the British and French governments are beginning to force their own utilities to make larger commitments to reprocessing. At the same time, Russia's Ministry of Atomic Energy (MinAtom), hopes to follow the lead of Britain and France and build a huge

(1500 tonnes/yr) new reprocessing plant at Krasnoyarsk-26 with foreign financing from countries such as South Korea and Taiwan. This proposal has triggered considerable resistance in Russia's environmental community, which is concerned that the Ministry is trying to make its reprocessing contracts more attractive by offering to keep foreign high-level waste—something which MinAtom, in fact, recently did to obtain a Hungarian reprocessing contract for its existing small reprocessing plant at Chelyabinsk-65. In all three countries, the political imperative is to maintain the employment of work forces in government-owned companies. This is a familiar phenomenon in the United States, where weapons are manufactured that are not needed.

Interim Spent Fuel Storage

Given that the economic value of the plutonium and uranium in spent fuel does not justify the cost of reprocessing at today's prices of uranium and separative work, reprocessing advocates have adopted the argument of the anti-nuclear movement that it would be irresponsible to dispose of plutonium and other long-lived transuranic isotopes underground. It is also argued that burial of spent fuel would create "plutonium mines" which could ease access to nuclear weapons materials in the future.

However, the countries that have adopted a once-through fuel cycle, are not, in fact, yet disposing their spent fuel irreversibly underground. Because of the concerns of their environmental communities, they are moving forward very slowly. Their spent fuel is typically expected to stay in interim or retrievable storage for at least 50 years.

Nor are the countries that are reprocessing commercially rushing to dispose of the resulting vitrified high-level waste (HLW) irreversibly underground. British Nuclear Fuel Limited has, for example, contracted for the storage of Scottish Nuclear's spent fuel and/or the residual high-level waste "until the year 2086 or until a suitable repository is available."[9] Environmentalists have not been persuaded that it is less hazardous to place vitrified HLW than spent fuel underground. And they may be right—given the fact that the long-lived fission products in the HLW: Tc-99 (0.2-million year half-life), I-129 (17 million years); and Cs-135 (3 million years) are much more soluble and therefore more mobile with ground water, through the food chain and finally into the human body, than plutonium oxide.[10]

Much of the plutonium that is being recovered by commercial reprocessing is also going into long-term interim storage. All of the more than 50 tonnes of plutonium that has been separated by Britain from Magnox fuel over the past 30 years is in long-term interim storage at Sellafield. Presumably the plutonium that is to be separated from the spent fuel of Britain's AGRs will be stored there as well. Similarly, all the 30 tonnes of LWR plutonium that has been recovered at Russia's Mayak reprocessing plant is in storage there. A stockpile of foreign plutonium is accumulating in Britain and France as well—because the rate of separation of this plutonium exceeds by far world capacity to fabricate the plutonium into MOX and because some countries—most notably Japan—have not yet licensed sufficient reactor capacity to absorb the MOX as fast as it is produced.

And then, of course, there is the 150 tonnes or so of surplus plutonium from dismantled U.S. and Russian nuclear warheads accumulating in interim storage as well.

Given that reprocessing is not accelerating the permanent disposal of high-level waste and is exacerbating the problem of excess separated plutonium, it would appear to make sense to reduce the rate of reprocessing at least until the huge surplus of separated plutonium is dealt with and the debate over the relative risks of underground disposal of spent fuel and glassified high-level waste are decided.

The absurdity of reprocessing under current conditions can be illustrated by a suggestion that was made to Britain when it was debating the operation of the new THORP reprocessing plant. It was noted that the prepaid reprocessing contracts with which Britain had built THORP could be satisfied without turning the plant on. Instead of turning the foreign spent fuel into separated plutonium and high-level waste, Britain could simply store the foreign spent fuel and send its foreign customers separated plutonium and HLW from its own stocks. It would thereby, in effect, have converted the unstable metal Magnox fuel which it had reprocessed into a much smaller tonnage of stable oxide fuel, creating for itself the option of direct disposal, while using the remaining funds owed under the reprocessing contracts to mothball the THORP plant and employ its workforce on some more useful activity.

Unfortunately, this alternative was not considered seriously. The British and the Japanese establishments were too committed to winning the fight to open THORP—and the Rokkashio plant thereafter.

Separated Plutonium and the Danger of Nuclear Terrorism

Why do people like myself, who work primarily on nuclear arms control and nonproliferation policy issues, concern themselves about national choices of nuclear fuel cycle for nuclear power? The main reason today is that separated plutonium is much easier to steal than plutonium in spent nuclear fuel. This is illustrated by the situation in Russia, where the stresses of a very difficult economic and political transition have resulted in the potential for large-scale theft of separated plutonium and highly-enriched uranium.

To illustrate the dangers of long-term stockpiling of separated plutonium, consider the fact that, at the Mayak reprocessing plant in the Urals, 30,000 kg of reactor-grade plutonium are stored in about 12,000 coffee-pot-sized containers in an ordinary building. The plutonium in two to three of these containers would be sufficient to make a nuclear explosive. The gamma and neutron dose rates from the containers are low enough so that they could be handled by terrorists without a significant amount of shielding.

In contrast, if one were to try to steal the same amount of plutonium in the spent fuel from a pressurized water reactor, it would be necessary first to steal a large highly-radioactive fuel assembly weighing hundreds of kilograms, which would give anyone standing nearby without shielding a lethal dose of radiation in on the order of ten minutes.[11] In order to transport it, it would be necessary to put it into a heavily shielded cask weighing tens of tons. And recovering the plutonium from the fuel assembly would require a facility that could chop up the fuel, dissolve it, and chemically recover the plutonium from the solution—all remotely behind heavy shielding—i.e., a reprocessing facility. Only after all that would the plutonium become as accessible to black-marketeers and terrorists as already-separated plutonium.

Currently, theft by black-marketeers of plutonium is not a major concern in the U.S., Western Europe or Japan. However, commercial reprocessing in Western Europe is used to justify reprocessing in Russia, and commercial reprocessing in Japan was used to justify reprocessing in North Korea—and might in the future be used to justify reprocessing in South Korea and China. In the past, plans for commercial reprocessing in the U.S. and Western Europe were used to justify reprocessing in India and proposals for reprocessing in Argentina, Brazil, South Korea, Pakistan and Taiwan—all of which were interested in acquiring nuclear weapons at the time. In the future, another reprocessing country will probably undergo a convulsion such as that currently gripping Russia. Where are the benefits from reprocessing that justify all these security risks? The risk-benefit balance may be different 50 or 100 years hence but that does not justify reprocessing today.

The Weapons-Usability of Reactor-Grade Plutonium

One of the reasons given by reprocessing advocates for their lack of concern about the potential for nuclear proliferation or nuclear terrorism resulting from the separation of plutonium from spent LWR fuel is that reactor-grade plutonium is not weapons useable. Thus, recently, in the September 1994 Financial Times Forum on "Crucial Issues in Managing the Fuel Cycle," Cogema Vice President, Jean-Pierre Rougeau (at that time also Chairman of the French Nuclear Energy Society) stated that: "reactor-grade plutonium is not realistically a potential weapons material . . . it is—practically speaking—virtually impossible to convert reactor-grade plutonium to military use."

Such statements are made despite briefings to the contrary by U.S. weapons designers for almost 20 years. Indeed, this intransigence was evident from the very beginning. One Los Alamos weapons designer told me that the response from leaders of the French nuclear-energy establishment to the first U.S. briefing in 1977 was, "No matter what you say, our plutonium is innocent!"

Well reactor-grade plutonium is not innocent! As has been explained in detail in an authoritative unclassified publication by Carson Mark, head of the Los Alamos Theory group from 1947-1972, if reactor-grade plutonium were substituted for the weapon-grade plutonium in the 1945 Nagasaki bomb, the yield at minimum would be on the order of 1000 tons of TNT—about one thousand times the power of the explosions under the World Trade Center and outside the Federal Building in Oklahoma City.[12] The results of a comprehensive review of post-Nagasaki designs—done at the request of the National Academy of Sciences plutonium-disposition study group[13] by weapons designers at the Livermore and Los Alamos Laboratories recently was summarized in the following unclassified statement:

> "Except for high purity Pu-238, plutonium of any isotopic composition, including that in spent fuel from commercial power reactors, can be used to make a nuclear weapon that is capable of significant nuclear yield. Design and construction of any nuclear weapon is a difficult task—but is a task that can be accomplished with a level of technical sophistication and computational capability that existed in the early 1950s at the nuclear-weapons design laboratories. Examination of designs typical of 1950s nuclear weapons indicate that replacing weapons grade plutonium with plutonium of other isotopic composition could have two results: it might decrease slightly the maximum yield of the weapon, and it might reduce the probability that maximum yield would be obtained in an explosion. *However, even in extreme cases, yields on the order of kilotons would result* [emphasis added]."

That is, if a nation—or a terrorist group—can construct a nuclear weapon with weapons-grade plutonium, it can construct one with reactor-grade plutonium. For this reason, the International Atomic Energy Agency, which has been advised on this matter by international weapons experts, does not distinguish between its requirements for safeguards on weapon-grade and reactor-grade plutonium.

References

1. *The Economics of the Nuclear Fuel Cycle* (Paris: OECD/NEA, 1994), Table 5.5.
2. *Uranium: Resources, Production and Demand* (Paris: OECD/NEA, 1993). Specifically, the cumulative resource estimates (in millions of tonnes U) at recovery costs of $130/kg or less is as follows: Reasonably Assured Resources (in known deposits)—2.1; plus Estimated Additional Resources (in known deposits)—3.0; plus other known resources, mostly in the former Soviet Union, where estimation methodology is not strictly consistent with NEA/IAEA resource terminology—4.4; plus estimated additional resources in known uranium areas—6.9; plus median estimates of undiscovered resources in areas of favorable geology— 8.9; plus undiscovered resources whose cost range has not been assigned: in China—10.7; plus Mongolia—12.0; plus South Africa—

13.2; plus Australia—15.8-17.1; plus other countries—16.4-17.7; plus uranium in phosphates recoverable as a byproduct (mostly in Morocco)—23.5-24.8.
3. Thomas Neff, M.I.T., private communication, June 1995.
4. Intergovernmental Panel on Climate Change (IPCC), Scenario IS92a, high nuclear/high demand scenario. The data in the IPCC scenario are given in exajoules per year of primary energy equivalent. These were converted to installed nuclear capacity on the basis of a capacity factor of 0.75 and a conversion of 10^7 joules per Kilowatt-hour (electric).
5. An annual uranium consumption of 120 tonnes U has been assumed per GWe-yr. This is appropriate for a 75 percent capacity factor, high burnup (53 MWt-day/kgU) and enrichment tails of 0.2 percent.
6. Huge new deposits of uranium with grades up to 30% uranium have recently been found in North Saskatchewan (private communication, D.E. Anderson, General Manager, Ontario Hydro Nuclear, June 19, 1995).
7. Harold A. Feiveson, Frank von Hippel and Robert H. Williams, "Fission Power: An Evolutionary Strategy," *Science* **203** (1979), pp. 330-337.
8. The capital cost of an LWR was assumed to be about $2000/kWe in current dollars (assuming that a 1976 dollar is worth $2.50 in 1995 dollars). Today, the capital cost for a passively-safe PWR is estimated at $1850/KWe [Palo Alto, Calif: Electric Power Research Institute, Technical Assessment Guide, EPRI TR-102275-V1R7, June 1993]. Assuming a capital recovery factor of 10%, the capital charge per kWh at a 75 percent capacity factor would be 2.8 cents/KWe-hr. Operating cost is estimated at 1 cent/kWh. Fuel cycle costs, excluding the cost of uranium purchase are approximately 0.4 cents/KWh [Paris: OECD/NEA, *The Economics of the Nuclear Fuel Cycle*, 1994, Table 5.7]. The contribution of $400/kg uranium to the cost of electricity would be approximately $(400 * 7.05) /(53 MWd/kg * 0.33 * 24,000 KWh/MWd) = 0.7 cents, where 7.05 kg of natural uranium are required to produce 1 kg of 4.4% U-235 at 0.1% tails assay.
9. *Nuclear Fuel*, May 22 1995, p. 4.
10. See, e.g. Thomas H. Pigford, "Actinide Burning and Waste Disposal," in *Proceedings of the First MIT International Conference on the Next Generation of Nuclear Power Technology*, Oct. 4-5, 1990.
11. See, e.g. W.R. Lloyd, M.K. Sheaffer, and W.G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air* (Lawrence Livermore National Laboratory, UCRL-ID-115199, 1994).
12. Carson Mark, "The Explosive Properties of Reactor-grade Plutonium," *Science and Global Security* **4**, 1993, pp. 111-128.
13. NAS Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (National Academy Press, 1994), pp. 32-33.